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## ROYAL SIGNALS AND RADAR ESTABLISHMENT

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SUMMARY

Discusses the problems that would arise if airspace users had the use of NAVSTAR or some other much better position-fixing aid than at present, and the uses that ATC could, or could not, make of this capability. There would be formidable transitional problems in the vertical plane, because NAVSTAR measures height from the Earth's centre whereas current altimeters measure atmosphere pressure. In either vertical or horizontal planes much work will be necessary to prove that the separation standards can be reduced at all. The paper discusses changes that might be possible in the ATC system should appreciable reductions in separation standards prove possible. NAVSTAR might form the basis of a collision avoidance system based on either the broadcast co-ordinates of each aircraft or on a time-frequency basis using NAVSTAR as the time reference. The latter scheme would offer protection of a fully-equipped aircraft against a threat that could not afford the expense of a NAVSTAR fit.

This paper is a contribution to the 29th AGARD GCP Symposium, Copenhagen, Oct 1979. It is issued as a memo to make it available earlier and in an unclassified document.

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PRECISION NAVIGATION FOR AIR TRAFFIC MANAGEMENT

S Ratcliffe

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1 INTRODUCTION

The present memo will be confined to the possible application of a precision absolute navaid, typified by NAVSTAR, to the management of predominately civil air traffic. Our primary concern will be with traffic in controlled airspace, where the potential benefits, eg from reduced separation standards, are probably greatest.

The adoption of NAVSTAR in civil air transport may come about simply because it is cheaper to fit NAVSTAR instead of many of the existing navaids. Its introduction need not be accompanied by any major change in the existing ATC system, which must, in any case, be tailored to the continuing use of present-day navaids by at least some of the traffic, until these can be phased-out, a process that may take 20 years or more. No doubt airlines and other users of NAVSTAR, as well as avionics salesmen, would protest that ATC was failing to make full use of the magnificent capability which NAVSTAR offers.

More probably, perhaps, it may transpire that NAVSTAR will represent an added expense to the aircraft operators, but it will then be argued that the expenditure is justified by the improvements in safety and in efficiency of operation. In either of the above situations, we need to discuss the benefits or otherwise of NAVSTAR in a modified traffic management system.

Let us suppose then, that NAVSTAR is available for general use. The accuracy obtainable will depend on the operating modes which are available to the given class of user, and on other factors. For the purposes of the present discussion, however, we will assume that position fixes (in NAVSTAR co-ordinates) are available, at an adequate data rate, to an accuracy of a few tens of metres. We can now ask how such a system could be used in air traffic management. It will be found, throughout much of the present paper, that this approach gives rise to more questions than answers.

An incidental property of NAVSTAR is that it is an area navigation system, but the rather well-worn arguments about RNAV will not be again discussed in the present paper, since RNAV ability can be provided even with any VOR or DME and an airborne computer less elaborate than that needed for NAVSTAR.

## 2 NAVSTAR AND SEPARATION STANDARDS

The obvious way of exploiting great navigational accuracy is to reduce separation standards. We will discuss separately the exploitation of improved position-fixing accuracy in plan and in the vertical plane. Given a system based on measuring range from a number of satellites, it is probably impossible to determine position with any accuracy without finding it in all three dimensions, together with time. NAVSTAR also supplies the three components of velocity. To exploit this information in the vertical and horizontal planes involves different problems.

It should be remarked that a reduction in separation standards can only be achieved in areas where the device has been widely adopted. If only a fraction "k" of all aircraft carry the new system, the probability that at least one aircraft in any random pair is not carrying the new system will be  $(1-k^2)$ . For example, if 90% of the aircraft are fitted, 20% of all encounters will involve at least one aircraft that is not. There is a need for altruism on the part of any airspace user who fits a new type of navaid solely on the grounds that its general adoption will eventually make possible a reduction in separation standards.

Once the new navigation system is in service and important features such as reporting points and airfields have been mapped in NAVSTAR co-ordinates, there is no obvious traffic management problem if aircraft wish to use the navaid to determine their position in plan.

Consider the separation standards in the horizontal plane in a region where there is no independent radar surveillance system. Considerable theoretical study has been carried out for the parallel-track structure over the Atlantic, notably by Reich (1,2,3) and his colleagues at the Royal Aircraft Establishment in the UK. Later work is continuing under the aegis of the ICAO North Atlantic Systems Planning Group. Such practical data as is available on cross-track navigational error is derived from measurements made when aircraft come into radar cover on leaving the Atlantic track system. The technique requires a radar accuracy somewhat better than the navigational errors to be measured and there is little possibility of achieving NAVSTAR accuracy with any medium- or long-range ground radar system. Probably the only checks possible will require the aircraft to fly over some specially instrumented range which only works well at fairly high elevation angles.

Early results on NAVSTAR accuracy should be available from military trials, but such trials are likely to concentrate on operation in the P-mode, the results may not readily be released to civilian agencies, and for military purposes the emphasis is likely to be on the errors that occur with moderate probability, rather than on the blunders on the tails of the probability distribution which are our major concern. The total navigational and flight control system with which we are eventually concerned, is, in any event, likely to differ in many respects from that used by the military. The work of building confidence in NAVSTAR will therefore be slow and difficult.

If the navigation performance is normally much better than is needed for the separation standard in use, either because of the difficulty in building up confidence in the system or because there is no case for a reduction in separation, the unnecessary accuracy may have an adverse effect on safety. Consider for example an aircraft that for some reason or other departs from the cleared flight level. The risk of collision with an aircraft at the next level increases with the precision with which both aircraft are flying a common track. A possible solution would be to cause some deliberate dispersion about the nominal values.

A special case of particular interest arises on the N Atlantic where there is a ruling that the latitude of all waypoints for E and W traffic must be an integer multiple of  $1^{\circ}$ . Ref (4) indicates that a major source of blunders in aircraft with computer-aided navigation is errors by the crew inputting waypoint data on a keyboard. The effect of the "multiples of  $1^{\circ}$ " rule is to produce a high risk that the erroneous waypoint will lie on the track of another aircraft. It will be difficult totally to avoid the in-flight insertion of waypoint parameters. If these same values must also be inserted manually into an ATC computer the risks are even greater.

Designers of automated banking systems are careful to arrange that account reference numbers contain self-checking features so that the clerks and the computer can easily check for errors such as the transposition of two digits. Perhaps there is a need for corresponding measures to make waypoint co-ordinates self-checking. The relevance of this point to the immediate argument is that measures to increase the number of tracks or to introduce some measure of dispersion about existing tracks will almost certainly involve some increase in the complexity of the co-ordinates that must be exchanged between ATC and the aircraft, and in the length of the messages that must be input to the various computers. Consider now the situation when the aircraft are within radar coverage. It was earlier pointed out that the assumed accuracy of NAVSTAR is far higher than that of existing surveillance systems, or indeed of any likely area surveillance system that is based on the earth's surface and therefore surrounded by close-in reflectors. If all aircraft could be relied on to have a serviceable NAVSTAR system, then it would be possible to base control on air-ground telemetered position data. The difficulties are those of making the transition from the present system and of proving to an adequate confidence level that the system is reliably accurate. Clearly the first of these problems has to be overcome before we could accumulate enough data to cast light on the second.

It may seem intuitively obvious that two aircraft on nominally different tracks are more safely separated if there is radar surveillance. Lloyd (4) considering opposing direction parallel traffic streams has challenged this supposition. In the Lloyd model, a sufficiently safe separation between two tracks on which aircraft are flying with cross-track errors having a double-exponential distribution with an s.d. of 0.5 NM is 5.1 NM. If radar monitoring were introduced, Lloyd assumes a total radar error in assessing the lateral separation of a pair of aircraft is 1 NM, and, rather charitably, that the radar is incapable of large errors. Under these assumptions, the radar intervention rate would be 0.035, ie the controller would have to intervene, unnecessarily, to "correct" the track of 3.5% of all aircraft movements. If this intervention rate is not tolerable the track spacing would have to be increased. A more general and rigorous treatment of the problem is still awaited. In Lloyd's study, the navaid was not much more accurate than the radar. NAVSTAR poses the problem in a more acute form. Perhaps the only effective form of ground surveillance now possible is to telemeter to the ground the NAVSTAR co-ordinates. This makes it possible on the ground to detect discrepancies due to data input blunders, or failures in the flight control system, between the planned path and that being flown, but there is no longer any independent cross-check on the navaid. Further, if the ground monitoring system is to consist of a human controller who detects failures in the flight control system and dictates corrective action, by voice, to the pilot, it is unlikely that the separations can be reduced much below their present values, if the controller is to have time to take effective action.

In the present ATC system there is a rough match between the accuracy of the navaids and of the surveillance system, and the separation standards are also consistent with the time needed by the controller, in an orderly traffic situation,

to recognise when something goes wrong and to take effective remedial action. Any attempt to exploit the greater accuracy of NAVSTAR will throw open very wide questions about the functions of, and justification for, a ground ATC system.

Coming now to the vertical plane, we have some additional problems. Historically, because aircraft height and plan position could only be determined by different means and to very different orders of accuracy, a traffic system has grown up which assumes that a safe separation in plan is very many times greater than a safe separation in the vertical, 5 NM rather than 1000 ft say. Because NAVSTAR achieves approximately the same accuracy in all three dimensions, this approach may need to be reconsidered. For example, the earlier discussion about the horizontal plane would probably still hold if the GPS plan positions had random errors of the order of 100 m, or so. NAVSTAR-derived heights would, however, then be no better than those from a pressure altimeter.

The other new factor, of course, is that NAVSTAR defines position in NAVSTAR co-ordinates. In the horizontal plane we have only to establish the position of existing reference points in global co-ordinates. In the vertical plane the present flight levels are based on a quantity that NAVSTAR cannot measure. By whatever means we establish an equivalence between NAVSTAR height and flight level, a mixed system is likely to require an increase rather than a decrease in separation standards.

It should be remarked however, that in NAVSTAR co-ordinates it is possible to define, once and for all, the minimum safe altitude which can be used in a given area. This information may be made available in the aircraft either by looking-up a table carried on-board, or remoted from a ground station. This technique will work even if ATC and the pilots continue to work with pressure levels, as at present, and perhaps this is one area where NAVSTAR could make an immediate contribution to flight safety.

The safe separation between aircraft is determined by the accuracy with which they can fly a given track, and not merely their ability to detect departures from it. In the limit one factor that determines track keeping accuracy is the ability of the aircraft to compensate for the effects of an atmospheric gust, and there is a need for study of the worst-case meteorological conditions and their effect on safe separation standards.

### 3 EXPLOITATION BY ATC OF REDUCED SEPARATION STANDARDS

It will be assumed that the adoption of NAVSTAR would have little effect on vertical separation standards, but that it should make possible a substantial reduction in lateral spacing. Unless the improved track-keeping accuracy is accompanied by a major improvement in time-keeping along track, a possibility that will be discussed later, traffic on intersecting routes are unlikely to be able to share a common flight level, since if it is necessary to monitor the relative position of aircraft on crossing routes, it will be necessary to leave time for remedial action in the event of conflict, and the end result would probably differ little from present-day procedures. The same argument applies to along track spacing, but this latter problem can be evaded by providing a multiplicity of parallel tracks.

It is in the complex TMA's of today that the ATC problems are most difficult, because of the large number of potential interactions between routes flown by climbing and descending traffic. We have not undertaken the formidable task of redesigning even one major TMA to determine the payoff from the widespread adoption by the air carriers of a navaid having a significantly higher accuracy. What becomes clear from even a brief examination of the problem is that, given

existing methods of ATC, attempts at closing up the spacing will soon hit the limitation mentioned earlier, the need to keep aircraft far enough apart to allow ATC time to detect conflicts or blunders and to take remedial action.

The alternative to the "tactical" approach to ATC, based largely on a pairwise comparison of aircraft positions, is a "strategic" approach which attempts to reserve a safe path for each aircraft for a significant part of the total flight. Such a system was proposed by Weiss (6) and by Stratton (7). Each aircraft is given a route which is separated from all others, like the inside of a strand of spaghetti in a bowl. The function of the ATC organisation is to assign routes to aircraft, to monitor adherence to the plan, en route, and to deal with any errors or emergencies.

The traffic capacity of the airspace, under the Weiss scheme, depends on the cross-sectional area of each "flight-tube" and on the length of time for which a given tube is allowed to reserve the airspace. Weiss apparently proposed to exercise tight control over the timing of the flight, but more recent studies of the problem (8) suggest that operation to a tight time-table would involve considerable penalties to the airlines, in guaranteeing that an aircraft would be ready for push-back at a given time. Even if we were content with only 80% successes in meeting the time-table the airline would have to add an additional 10 minute buffer to the turn-round time, which amounts to a 5% DOC penalty for a typical European operation. There are further time uncertainties after the aircraft has requested pushback. For example, an aircraft leaving Gatwick via Midhurst would have to face an extra 5 mins taxi and an extra 2 mins flight if the runway direction changed from 08 to 26 after the strategy was planned. Further operating penalties are entailed if the planned cruising speed and flight level are to be such that the aircraft has capability safely to increase or decrease airspeed by an amount great enough to compensate for wind, even, let alone any initial delay. The more realistic version of the Weiss scheme might allow reasonable latitude, say 30 mins, on the time at which an aircraft passed a given point on his flight tube.

Weiss spoke in terms of each large metropolitan airport having 30-200 flight tubes leading to each of about 100 different cities, ie about 10,000 flight tubes per airport. It was assumed that the accuracy with which an aircraft can stay on track is such that 500 ft is a safe separation between his flight tubes. If the system is to be provided with ground monitoring and provision for tactical intervention to deal with emergencies such as engine or pressurisation failures or the need to avoid Cu-Nimb, it may well be that the safe separation between tubes is such that we wind up with a system having less capacity than at present.

#### 4 OTHER POSSIBLE APPLICATIONS OF NAVSTAR-GPS

Earlier in the paper we discussed a possible ground monitoring system based on NAVSTAR data telemetered from the aircraft to the ground. It was argued that aircraft spacings had to leave time for the ground-based controller to recognise that a problem had arisen and to provide a solution. With a system having a strong procedural basis, the emphasis is on checking that an aircraft's position is consistent with a plan that has been laid down earlier. It is an advantage of such a system that the checking process can be readily automated, but in this situation it is less clear why the ground organisation should be involved so intimately in the process. No matter whether the departure of the aircraft from the planned trajectory is due to an aircrew blunder or to a failure in the navaid or in the flight control system, it is the pilot who should be informed and who must take the remedial action. Ford (9) has argued that the pilot should also be responsible for monitoring his position relative to his neighbours,

and correcting his path as necessary. Since each aircraft could telemeter not only its position and velocity but also immediate intention (eg "turning right") the monitoring process would have much better input data than that available to present-day radar controllers. All these processes would have to take place within the framework of a central strategy derived on the ground but with relevant portions of the overall plan made available in the aircraft and displayed in some convenient format on the Air Traffic Situation Display.

Without proposing such a dramatic change, it would be possible for NAVSTAR aircraft to provide themselves with a collision-warning facility to be used as an adjunct to ATC, by eavesdropping on the air-ground telemetered NAVSTAR data. Such a system would serve only to prevent collision between pairs of aircraft both of which carried NAVSTAR.

An alternative approach to collision avoidance is the ATA time-frequency system (10), certain simplifications being possible if NAVSTAR is in service. Each aircraft broadcasts, at intervals of a few seconds, a time signal (derived from NAVSTAR time) from which another aircraft (also having access to NAVSTAR time) can measure range, a message giving height and immediate intention, and a burst of CW (on a frequency accurately controlled by reference to the NAVSTAR signals) from which another aircraft can determine range-rate by doppler measurement.

Both this system and that described earlier, in which an aircraft broadcasts its NAVSTAR position, can rely on NAVSTAR time to define a series of perhaps several thousand time-slots each of which is available for one aircraft to broadcast its data at intervals of a few seconds. There is a technique which enables aircraft automatically to search for and occupy a previously empty slot.

The elimination of the need for accurate airborne clocks represents an appreciable improvement over the original ATA scheme, the only snag being that the airborne collision avoidance device offers no protection in the event of a failure in NAVSTAR.

The merit of the ATA scheme is that the fully-equipped aircraft can be protected against a general-aviation threat which carries only a simple time-frequency transponder. The GA aircraft need not carry part of NAVSTAR, ref. (10) explains how an adequate time reference can be derived from the signals from a fully-equipped aircraft. The GA aircraft receives no collision warning, the escape manoeuvre is left to the fully-equipped aircraft.

The general aviation user must nevertheless pay for an additional transponder. This protects against collision with air carriers, the biggest collision risk which the latter have to face. The main collision risk to a GA aircraft is collision with another aircraft in the same category, and the simple time-frequency transponder offers no protection even if both aircraft are fitted.

In this respect the time-frequency device is at a disadvantage with respect to BCAS, since all the GA aircraft need carry to protect the air carrier is the SSR equipment that ATC is beginning to demand anyway. This may not protect two GA aircraft from collision, but at least there is no additional expense.

The general difficulty with airborne collision-avoidance devices is that they don't know what any ground organisation is trying to do with the traffic. There are some difficult compromises to be made in an attempt at providing adequate escape time without provoking clashes between the airborne system and ATC. These compromises will not be easier if they must apply world-wide.

## 5 CONCLUSION

It is possible that NAVSTAR-GPS will be adopted in civil aviation. The advantages of a navaid which gives good cover down to ground-level more or less worldwide are considerable. The advent of a common time-reference is a by-product that may find numerous applications.

The present paper has been concerned with the possibility that there may become available to air transport generally a navaid which makes possible significantly better track-keeping than is generally available at present. The navaid need not be NAVSTAR although the paper uses this example. Although ADSEL-DABS (11,12) offers the possibility of an improvement in the accuracy and reliability of the surveillance system on which ATC is based, the day may come when the general track-keeping ability of the aircraft population is better than the tracking capability of the surveillance system, and some re-thinking of the whole ATC concept may be necessary.

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